

Production of the bottom analogues and the spin partner of the $X(3872)$ at hadron colliders

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Using the Monte Carlo event generator tools Pythia and Herwig, we simulate the production of bottom/charm meson and antimeson pairs at hadron colliders in proton-proton/antiproton collisions. With these results, we derive an estimate for the production rates of the bottom analogues and the spin partner of the $X(3872)$ as hadronic molecules at the LHC and Tevatron experiments. We find that the cross sections for these processes are at the nb level, and that the current and future data sets from the Tevatron and LHC experiments offer a significant discovery potential. We further point out that the X_b/X_{b2} should be reconstructed in the $\gamma\Upsilon(nS)(n = 1, 2, 3)$, $\Upsilon(1S)\pi^+\pi^-\pi^0$, or $\chi_{bJ}\pi^+\pi^-$ instead of the $\Upsilon(nS)\pi^+\pi^-$ final states.

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I. INTRODUCTION

As the B factories and high energy hadron colliders have accumulated unprecedented data samples, a dramatic progress has been made in hadron spectroscopy in the past decade. Especially, in the mass region of heavy quarkonia, a number of new and unexpected structures have been discovered at these experimental facilities. Many of them defy an ordinary charmonium interpretation, among which the $X(3872)$ has received the most intensive attention [1] so far.

The $X(3872)$ was first discovered by the Belle Collaboration in B decays at the e^+e^- collider located at KEK [2] and later confirmed by the BaBar Collaboration [3] in the same channel. It can also be copiously produced in high energy proton-proton/antiproton collisions at the Tevatron [4, 5] and LHC [6, 7]. This meson is peculiar in several aspects, and its nature is still under debate. The total width is tiny compared to typical hadronic widths and only an upper bound has been set: $\Gamma < 1.2$ MeV [8]. The mass lies in the extreme close vicinity to the $D^0\bar{D}^{*0}$ threshold, $M_{X(3872)} - M_{D^0} - M_{D^{*0}} = (-0.12 \pm 0.24)$ MeV [9], which leads to speculations of the $X(3872)$ as a hadronic molecule—either a $D\bar{D}^*$ loosely bound state [10] or a virtual state [11]. Furthermore, a large isospin breaking is found in its decays: the process $X(3872) \rightarrow J/\psi\pi^+\pi^-$ via a virtual ρ^0 and the process $X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$ via a virtual ω have similar partial widths [8]. Evidence for different rates of charged and neutral B decays into $X(3872)$ was also found [12].

These facts have stimulated great interest in understanding the nature, production and de-

cays of the $X(3872)$. An important aspect involves the discrimination of a compact multiquark configuration and a loosely bound hadronic molecule configuration. Recent calculations of the hadroproduction rates at the LHC based on nonrelativistic QCD indicate that the $X(3872)$ could hardly be an ordinary charmonium $\chi_{c1}(2P)$ [13, 14], while there are sizable disagreements in theoretical predictions in the molecule picture [15–19].

To clarify the intriguing properties and finally decipher the internal nature, more accurate data and new processes involving the production and decays of the $X(3872)$ will be helpful. For instance, one may obtain useful information on the flavor content of the $X(3872)$ from precise measurements of decays of neutral/charged B mesons into the $X(3872)$ associated with neutral/charged K^* mesons.

On the other hand, it is also expedient to look for the possible analogue of the $X(3872)$ in the bottom sector, referred to as X_b following the notation suggested in Ref. [20]. If such a state exists, measurements of its properties would assist us in understanding the formation of the $X(3872)$ as the underlying interaction is expected to respect heavy flavor symmetry. In fact, the existence of such a state was predicted in both the tetraquark model [21] and hadronic molecular calculations [22–24]. The mass of the lowest-lying $1^{++} \bar{b}q\bar{b}q$ tetraquark was predicted to be 10504 MeV in Ref. [21], while the mass of the $B\bar{B}^*$ molecule based on the mass of the $X(3872)$ is a few tens of MeV higher [23, 24]. In Ref. [23], the mass was predicted to be (10580^{+9}_{-8}) MeV for a typical cut-off, corresponding to a binding energy of (24^{+8}_{-9}) MeV.

Notice that there is a big difference between the predicted X_b and the $X(3872)$. The distance of the mass of the $X(3872)$ to the $D^0\bar{D}^{*0}$ threshold is much smaller than the distance to the D^+D^{*-} threshold. This difference leaves its imprint in the wave function at short distances through the charmed meson loops so that a sizeable isospin breaking effect is expected. However, the mass difference between the charged and neutral B mesons is only (0.32 ± 0.06) MeV [8], and the binding energy of the $B\bar{B}^*$ system may be larger than that in the charmed sector due to a larger reduced mass. In addition, while the isospin breaking observed in the $X(3872)$ decays into J/ψ and two/three pions can be largely explained by the phase space difference between the $X(3872) \rightarrow J/\psi\rho$ and the $X(3872) \rightarrow J/\psi\omega$ [25], the phase space difference between the $\Upsilon\rho$ and $\Upsilon\omega$ systems will be negligible since the mass splitting between the X_b and the $\Upsilon(1S)$ is definitely larger than 1 GeV. Therefore, we expect that the isospin breaking effects would be much smaller for the X_b than that for the $X(3872)$. Consequently, the X_b should be an isosinglet state to a very good approximation, in line with the predictions in Refs. [22–24].

Since the mass of the X_b is larger than 10 GeV and its quantum numbers J^{PC} are 1^{++} , it is unlikely to be discovered at the current electron-positron collision facilities, though the prospect for an observation in the $\Upsilon(5S, 6S)$ radiative decays at the Super KEKB in future may be bright due to the expected large data sets, of order 50 ab^{-1} [26]. In this paper, we will follow the previous work on the search for exotic states at hadron colliders [16–19, 27–29] and focus primarily on the production of the X_b and its spin partner, a $B^*\bar{B}^*$ molecule with $J^{PC} = 2^{++}$, denoted as X_{b2} , at

the LHC and the Tevatron. Results on the production of the spin partner of the $X(3872)$, X_{c2} with $J^{PC} = 2^{++}$, will also be given. Notice that due to heavy quark spin symmetry, the binding energies of the X_{b2} and X_{c2} are similar to those of the X_b and $X(3872)$, respectively.

This paper is organized as follows. We begin in Sec. II by discussing the factorization formula for the $pp/\bar{p} \rightarrow X_b/X_{b2}$ (both pp and $p\bar{p}$ will be written as pp for simplicity in the following) amplitudes in case that the X_b/X_{b2} is a bound state not far from threshold. Our numerical results for the cross sections of the inclusive processes $pp \rightarrow B^{(*)}\bar{B}^*$ and $pp \rightarrow X_b/X_{b2}$ are presented in Sec. III. The last section contains a brief summary.

II. HADROPRODUCTION

Consider an S -wave loosely bound state with a binding energy b . If the scattering length $a = 1/\sqrt{2\mu b}$, where μ is the reduced mass of the constituents, is much larger than the range of forces, the system has universal properties determined by solely by the scattering length a [30]. In particular, the energy dependence of the S -wave scattering amplitude in the region close to the threshold should be described by (see, for instance, Ref. [30])

$$f(E) = \frac{1}{-1/a + \sqrt{-2\mu E - i\epsilon}}, \quad (1)$$

if there is no any other nearby resonance with the same quantum numbers. Here, E is the energy relative to the scattering threshold.

Based on the universal amplitudes ¹ and the Migdal-Watson theorem, the authors in Refs. [18, 19] have derived a formula which may be used as an estimate for the cross section of the inclusive production of an S -wave loosely bound hadronic molecule, and used it in the case of the process $pp \rightarrow X(3872)$. If the binding energy of the X_b , E_{X_b} , is small so that the the binding momentum $\sqrt{2\mu E_{X_b}}$ is much smaller than the mass of the pion, the lightest meson which can be exchanged between a pseudoscalar and a vector bottom mesons, one can use the same formula to estimate the production cross section of the X_b , which reads

$$\sigma(X_b) \approx \sigma(pp \rightarrow B\bar{B}^*[k < \Lambda]) \frac{6\pi\sqrt{2\mu E_{X_b}}}{\Lambda}, \quad (2)$$

where $\sigma(pp \rightarrow B\bar{B}^*[k < \Lambda])$ is the cross section for the inclusive process $pp \rightarrow B\bar{B}^*$ with the relative momentum of the B in the meson pair rest frame smaller than a cutoff $\Lambda \approx M_\pi$. This quantity will be estimated using Monte Carlo event generators in the following section.

The above formula is derived on the basis of factorization. In order to form a molecule, the mesonic constituents must be produced at first and have to move collinearly with a small relative momentum. Such configurations originate from the inclusive QCD process which contains a $\bar{Q}Q$

¹ One may also directly use the amplitudes derived in effective field theory [23]. However, for an order-of-magnitude estimate when the binding energy is small, it is sufficient to use Eq. (1).

pair with a similar relative momentum in the final state. Thus, at least a third parton needs to be produced in the recoil direction, which corresponds to a $2 \rightarrow 3$ parton process. In our explicit realization, the $2 \rightarrow 3$ process can be generated initially through hard scattering, and the parton shower will produce more quarks via soft radiations.

III. RESULTS AND DISCUSSIONS

Following our previous work [29], we use Madgraph [31] to generate the $2 \rightarrow 3$ partonic events with a pair of a heavy quark and an antiquark ($b\bar{b}$ or $c\bar{c}$) in the final states, and then pass them to the Monte Carlo event generators for hadronization. To improve the efficiency of the calculation, we apply the partonic cut for the transverse momentum $p_T > 2$ GeV for heavy quarks and light jets, $m_{b\bar{b}} < 11$ GeV ($k_{B\bar{B}^*} = 1.5$ GeV and $k_{B^*\bar{B}^*} = 1.4$ GeV at the hadron level), $m_{c\bar{c}} < 5$ GeV ($k_{D\bar{D}^*} = 1.6$ GeV and $k_{D^*\bar{D}^*} = 1.5$ GeV) and $\Delta R(b, \bar{b}) < 1$ ($\Delta R(c, \bar{c}) < 1$) where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ($\Delta\phi$ is the azimuthal angle difference and $\Delta\eta$ is the pseudo-rapidity difference of the $b\bar{b}$). We choose Herwig [32] and Pythia [33] as our hadronization generators, whose outputs are analyzed using the Rivet library [34].

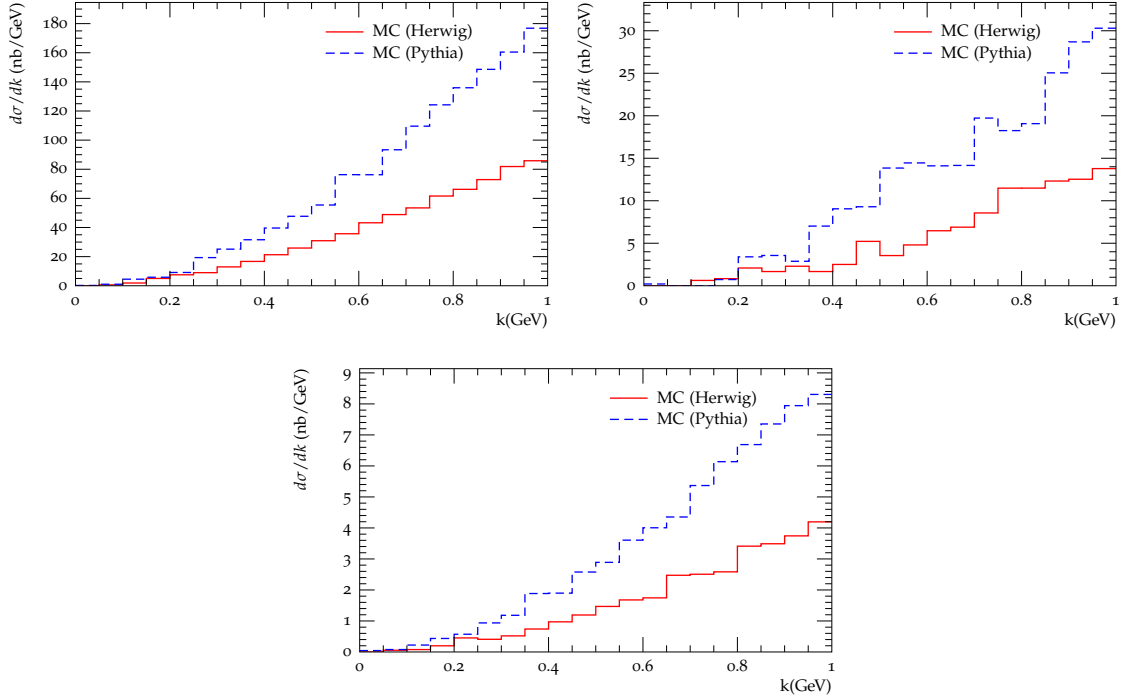


FIG. 1: Differential cross sections $d\sigma/dk$ (in units of nb/GeV) for the process $pp \rightarrow B^0 \bar{B}^{*0}$ at the LHC with $\sqrt{s} = 8$ TeV and at the Tevatron with $\sqrt{s} = 1.96$ TeV. The kinematic cuts in the first panel are used as $|y| < 2.5$ and $p_T > 5$ GeV, which lie in the phase-space regions of the ATLAS and CMS detectors, for the Tevatron experiments (CDF and D0) at 1.96 TeV (the last panel), we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for LHCb (the middle panel).

Based on 10^7 partonic events generated by Madgraph, we show the differential cross sections $d\sigma/dk$ (in units of nb/GeV) for the process $pp \rightarrow B^0 \bar{B}^{*0}$ in Fig. 1, and the ones for the reaction $pp \rightarrow B^{*0} \bar{B}^{*0}$ in Fig. 2 at the LHC with the center-of-mass energy $\sqrt{s} = 8$ TeV and at the Tevatron with $\sqrt{s} = 1.96$ TeV. The kinematic cuts are $|y| < 2.5$ and $p_T > 5$ GeV, where y and p_T are the rapidity and the transverse momentum of the bottom mesons, respectively, which lie in the phase space regions of the ATLAS and CMS detectors. For the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for the LHCb detector.

Notice that although the binding energies of the X_b and X_{b2} are normally predicted at the order of a few tens of MeV, the uncertainty could be of the same order as discussed in Ref. [23]. Since none of them has been observed, we will attempt to use three benchmark values: 1 MeV, 2 MeV and 5 MeV. In the case of 5 MeV, the binding momentum is already at the order of the pion mass, and the use of Eq. (2) bares a large uncertainty. However, since we are only interested in an order-of-magnitude estimate, such a treatment should suffice. For larger binding energies, the scattering amplitude in Eq. (1) does not apply and instead one should use the amplitudes predicted by effective field theory. For the X_{c2} , we will use 0.3 MeV (close to the upper bound of the data $M_{D^0} + M_{\bar{D}^{*0}} - M_{X(3872)} = (0.12 \pm 0.24)$ MeV [9]), 2 MeV and 5 MeV. Integrated cross sections (in units of nb) for the $pp \rightarrow X_b$, and $pp \rightarrow X_{b2}$ are collected in Tab. I. Results outside (inside) brackets are obtained using Herwig (Pythia). We have also checked the cross sections for the $pp \rightarrow X(3872)$ and found a qualitative agreement with Ref. [18] (in the ballpark of the results

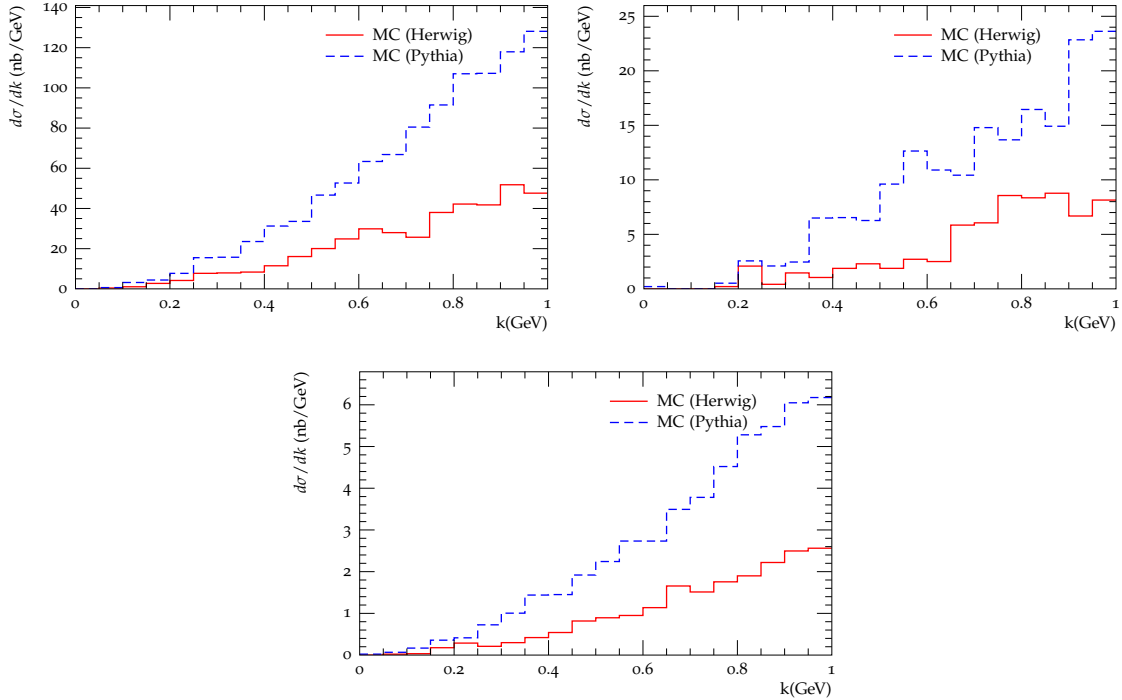


FIG. 2: Same as Fig. 1 but for the $B^* \bar{B}^*$ final state.

for the X_{c2} with a 0.3 MeV binding energy)². From the table, one sees that the cross sections for the X_{b2} is similar to those for the X_b , and the ones for the X_{c2} are two orders of magnitude larger.

TABLE I: Integrated cross sections (in units of nb) for the $pp/\bar{p} \rightarrow X_b$, and $pp/\bar{p} \rightarrow X_{b2}$ at the LHC and Tevatron. Results outside (inside) brackets are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV; for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for the LHCb. Since the binding energy is not measured, we use 1 MeV, 2 MeV and 5 MeV for illustration. For the X_{c2} , we choose 0.3 MeV, 2 MeV and 5 MeV.

X_b	$E_{X_b} = 1 \text{ MeV}$	$E_{X_b} = 2 \text{ MeV}$	$E_{X_b} = 5 \text{ MeV}$
Tevatron	0.04(0.09)	0.06(0.12)	0.09(0.19)
LHC 7	0.74(1.5)	1.1(2.1)	1.7(3.3)
LHCb 7	0.11(0.25)	0.16(0.36)	0.25(0.56)
LHC 8	0.9(1.7)	1.3(2.5)	2.(3.9)
LHCb 8	0.13(0.32)	0.19(0.45)	0.3(0.72)
LHC 14	1.7(3.1)	2.5(4.4)	3.9(6.9)
LHCb 14	0.31(0.64)	0.44(0.91)	0.7(1.4)
X_{b2}	$E_{X_{b2}} = 1 \text{ MeV}$	$E_{X_{b2}} = 2 \text{ MeV}$	$E_{X_{b2}} = 5 \text{ MeV}$
Tevatron	0.03(0.06)	0.04(0.09)	0.06(0.14)
LHC 7	0.47(1.1)	0.66(1.5)	1.(2.4)
LHCb 7	0.07(0.19)	0.1(0.27)	0.15(0.43)
LHC 8	0.53(1.3)	0.75(1.8)	1.2(2.9)
LHCb 8	0.08(0.24)	0.12(0.35)	0.19(0.55)
LHC 14	1.(2.3)	1.5(3.3)	2.3(5.2)
LHCb 14	0.19(0.48)	0.26(0.68)	0.42(1.1)
X_{c2}	$E_{X_{c2}} = 0.3 \text{ MeV}$	$E_{X_{c2}} = 2 \text{ MeV}$	$E_{X_{c2}} = 5 \text{ MeV}$
Tevatron	1.1(0.73)	2.7(1.9)	4.3(3.)
LHC 7	16(11)	42(29)	66(46)
LHCb 7	3.4(2.1)	8.8(5.4)	14(8.5)
LHC 8	19(13)	48(33)	76(52)
LHCb 8	3.7(2.4)	9.7(6.2)	15(9.8)
LHC 14	33(23)	85(60)	135(95)
LHCb 14	8.(4.9)	21(13)	33(20)

Recently, the CMS Collaboration has presented results of a first search for new bottomonium states, with the main focus on the X_b , decaying to $\Upsilon(1S)\pi^+\pi^-$. The search is based on a data sample corresponding to an integrated luminosity of 20.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ [35]. No evidence for the X_b is found, and the upper limit at a confidence level of 95% on the product of the production

² Ref. [18] used kinematic cuts at the parton level, while in this work we apply hadronic cuts which can be directly implemented on the experimental side.

cross section of the X_b and the decay branching fraction of $X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$ has been set to be

$$\frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)} < (0.009, 0.054) , \quad (3)$$

where the range corresponds to the variation of the X_b mass from 10 to 11 GeV.

Using the current experimental data on the $\sigma(pp \rightarrow \Upsilon(2S))$, we can convert the above ratio into the cross section which can be directly compared with our results. Since the masses of the $\Upsilon(2S)$ and X_b are not very different, it may be a good approximation to assume that the ratio given in Eq. (3) is insensitive to kinematic cuts. Using the CMS measurement in Ref. [36]:

$$\sigma(pp \rightarrow \Upsilon(2S))\mathcal{B}(\Upsilon(2S) \rightarrow \mu^+\mu^-) = (2.21 \pm 0.03^{+0.16}_{-0.14} \pm 0.09) \text{ nb}, \quad (4)$$

with the cuts $p_T < 50$ GeV and $|y| < 2.4$ for the $\Upsilon(2S)$, we get

$$\sigma(pp \rightarrow X_b)\mathcal{B}(X_b \rightarrow \Upsilon(1S)\pi^+\pi^-) < (0.18, 1.11) \text{ nb} . \quad (5)$$

Since the branching ratio $\mathcal{B}(X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)$ is expected to be tiny (see below), the above upper bound is much larger than our predictions.

As already discussed in the Introduction, the X_b and X_{b2} are probably isosinglets. In contrast to the $X(3872)$, the isospin breaking decays of these two states will be heavily suppressed. Thus, one cannot simply make an analogy to the $X(3872) \rightarrow J/\psi\pi^+\pi^-$ and try to search for the X_b in the $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ channels, as the isospin of the $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ systems is 1 when the quantum numbers are $J^{PC} = 1^{++}$. This could be the reason for the negative search result by the CMS Collaboration [35]. Possible channels which can be used to search for the X_b and X_{b2} include the $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$), $\Upsilon(1S)\pi^+\pi^-\pi^0$ and $\chi_{bJ}\pi^+\pi^-$. The X_{b2} can also decay into $B\bar{B}$ in a D -wave, and the decays of the X_{c2} are similar to those of the X_{b2} with the bottom being replaced by its charm analogue. The isospin breaking decay $X_{c2} \rightarrow J/\psi\pi^+\pi^-$ through an intermediate ρ meson should be largely suppressed compared with the decay of the $X(3872)$ into the same particles because the mass of the X_{c2} is about 140 MeV higher than that of the $X(3872)$, and the phase space difference between the $J/\psi\rho$ and $J/\psi\omega$ becomes tiny.

Compared with the pionic decays, the $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) final states are advantageous because no pion needs to be disentangled from the combinatorial background. The disadvantage is the low efficiency in reconstructing a photon at hadron colliders. Since the $X(3872)$ meson has a sizable partial decay width into the $J/\psi\gamma$ [8]

$$\mathcal{B}(X(3872) \rightarrow \gamma J/\psi) > 6 \times 10^{-3}, \quad (6)$$

presumably the branching ratio for the $X_b \rightarrow \gamma\Upsilon$ is of this order. If so, the cross section for the $pp \rightarrow X_b \rightarrow \gamma\Upsilon(1S) \rightarrow \gamma\mu^+\mu^-$ is of $\mathcal{O}(10 \text{ fb})$ or even larger when summing up the $\Upsilon(1S, 2S, 3S)$. Since the CMS and ATLAS Collaborations have accumulated more than 20 fb^{-1} data [37, 38], we expect at least a few hundred events. Less events will be collected at the LHCb detector due to

a smaller integrated luminosity, $\mathcal{O}(3 \text{ fb}^{-1})$ [39]. Nevertheless, the future prospect is bright since a data sample of about 3000 fb^{-1} , will be collected, for instance, by ATLAS after the upgrade [40].

Apart from the production rates, the nonresonant background contributions can also play an important role in the search for these molecular states at hadron colliders since a signal could be buried by a huge background. To investigate this issue, we consider the X_b as an example, which will be reconstructed in $\Upsilon + \gamma$ final states. In this process, the inclusive cross section $\sigma(pp \rightarrow \Upsilon + \text{anything})$ can serve as an upper bound for the background. It has been measured at $\sqrt{s} = 7 \text{ TeV}$ by the ATLAS Collaboration as [43]

$$\sigma(pp \rightarrow \Upsilon(1S)(\rightarrow \mu^+\mu^-) + \text{anything}) = (8.01 \pm 0.02 \pm 0.36 \pm 0.31) \text{ nb}, \quad (7)$$

with $p_T < 70 \text{ GeV}$ and $|y| < 2.25$. Our results in Tab. I show that the corresponding cross section for the $pp \rightarrow X_b$ is about 1 nb at $\sqrt{s} = 7 \text{ TeV}$. It is noteworthy to point out that our kinematic cuts in p_T are more stringent compared to the ones set by the ATLAS Collaboration. Using the integrated luminosity in 2012, 22 fb^{-1} [37], we have a lower bound estimate for the signal/background ratio

$$\frac{S}{\sqrt{B}} \gtrsim \frac{1 \times 22 \times 10^6 \times 2.6\% \times 10^{-2}}{\sqrt{8 \times 22 \times 10^6}} \simeq 0.4, \quad (8)$$

where 2.6% is the branching fraction of the $\Upsilon(1S) \rightarrow \mu^+\mu^-$ [8], and 10^{-2} is a rough estimate for the branching fraction of the $X_b \rightarrow \Upsilon(1S)\gamma$. The value of the signal/background ratio can be significantly enhanced in the data analysis by employing suitable kinematic cuts which can greatly suppress the background, and accumulating many more events based on the upcoming 3000fb^{-1} data [40].

IV. SUMMARY

In summary, we have made use of the Monte Carlo event generator tools Pythia and Herwig, and explored the inclusive processes $pp/\bar{p} \rightarrow B^0 \bar{B}^{*0}$ and $pp/\bar{p} \rightarrow B^{*0} \bar{B}^{*0}$ at hadron colliders. Based on the molecular picture, we have derived an estimate for the production rates of the X_b , X_{b2} and X_{c2} states, the bottom and spin partners of the $X(3872)$, at the LHC and Tevatron experiments. We found that the cross sections are at the nb level for the hidden bottom hadronic molecules X_b and X_{b2} , and two orders of magnitude larger for the X_{c2} . Therefore, one should be able to observe them at hadron colliders if they exist in the form discussed here. The channels which can be used to search for the X_b and X_{b2} include the $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$), $\Upsilon(1S)\pi^+\pi^-\pi^0$, $\chi_{bJ}\pi^+\pi^-$ and $B\bar{B}$ (the last one is only for the X_{b2}), and the channels for the X_{c2} is similar to those for the X_{b2} (with the bottom replaced by its charm analogue). In fact, both the ATLAS and D0 Collaborations reported an observation of the $\chi_b(3P)$ [41, 42], whose mass is $(10534 \pm 9) \text{ MeV}$ [8], slightly lower than the X_b and X_{b2} , in the $\Upsilon(1S, 2S)\gamma$ channels. A search for these states will provide very useful information

in understanding the $X(3872)$ and the interactions between heavy mesons. Especially, if the X_b , which is the most robust among the predictions in Ref. [23] based on heavy quark symmetries, cannot be found in any of these channels, it may imply a non-molecular nature for the $X(3872)$.

Acknowledgments

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